Defense Technical Information Center
Compilation Part Notice

ADP012478

TITLE: Concepts for Fieldable Electromagnetic Gun Barrels

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: 10th U.S. Army Gun Dynamics Symposium Proceedings

To order the complete compilation report, use: ADA404787

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012452 thru ADP012488

CONCEPTS FOR FIELDABLE ELECTROMAGNETIC GUN BARRELS

M. J. Hinton[1], A. Howard[2], N. R. Cooper[2], D. K. Wallington[3], and M. A. Firth[3]

[1] *Future Systems Technology Division (FST), DERA, Fort Halstead, UK*
[2] *Structures and Materials Centre, FST Division, DERA, Farnborough, UK*
[3] *Centre for Defence Technology, FST Division, DERA, Fort Halstead, UK*

Point of Contact: Professor M. J. Hinton, Director of Technology (Operations),
FST Division, Fort Halstead, Sevenoaks, Kent, TN14 7BP, UK
Telephone: 44 (0) 1959 514946
Fax: 44 (0) 1959 516059
e-mail: mjhinton@dera.gov.uk

The Defence Evaluation and Research Agency (DERA) is investigating EM gun technology on behalf of the United Kingdom Ministry of Defence for possible application to future armoured land vehicles. The UK has achieved considerable success with large calibre, laboratory-weight launchers at the Electromagnetic Launch Facility at Kirkcudbright. The development of 'fieldable' EM guns is less advanced, mirroring the picture elsewhere in the world. One approach taken by the UK has been to consider how technology, currently being applied to conventional (ie powder) gun barrels, can be combined with the best aspects of the laboratory EM barrels into fieldable EM launcher concepts. In this paper the new EM barrel concepts are compared with conventional barrels and laboratory EM launchers in terms of mass, flexural stiffness, muzzle droop and inductance gradient, the latter parameter being a key driver of launcher electrical efficiency. Both circular and non-circular bore shapes are considered. The role of lightweight, fibre composite containment structures is highlighted in order to produce weapons of comparable mass and muzzle droop to a conventional tank gun.

INTRODUCTION

Electromagnetic (EM) launch technology can be divided into the sub-categories of 'rail launchers' and 'induction launchers'. The latter can be further divided into 'coil guns/launchers' and 'linear induction launchers'. In recent years the majority of weapons related EM launch technology research, in the UK and around the world, has concentrated on rail launchers. Furthermore, the research has focussed upon the use of EM launch technology

for the hypervelocity launch of direct fire kinetic energy (KE) ammunition. The primary motivation is enhanced terminal effectiveness.

With the move towards improved strategic mobility, and consequently lighter platforms, the primary exploitation route for EM launch technology is currently considered to be as a main armament for a future land combat system. In addition to enhanced lethality, EM launch offers further benefits including (i) a reduction in trunnion pull (recoil impulse) compared with an equivalent performance conventional (ie powder) gun and (ii) the elimination of chemical propellant, providing improved survivability, enhanced tactical mobility (reduced logistic drag) and increased battle tempo.

The requirements for such a weapon system include the need for compatibility with future light(er) weight vehicles (Ref 1) and the lethality to defeat future enemy combat systems. Also desirable would be any improvements accrued in survivability or sustainability due to adoption of the weapon system. EM launch provides enhanced target defeat through the hypervelocity launch of KE projectiles. Coupled with novel KE projectile development, this should ensure robust defeat of enemy targets.

EM launch technology has been studied at various times in the past, and during the recent era (1980s onwards) a considerable amount of information has been gathered. It is evident from the literature (Refs 2, 3 and 4) that the current status of much of the required technology (power supply, launcher, launch package) is still at the experimental stage. Consequently there is a something of a gap between current research programmes and that which is required to achieve the tactical advantages in the operational environments described above.

Considering specifically EM gun barrel technology, successful launchers (ie those capable of firing tactical projectiles at hypervelocity) remain as heavyweight laboratory structures which would be impossible to deploy in combat. Much lighter designs are required - similar in mass to conventional powder guns.

In parallel with EM launcher development, the UK has investigated the technology required to lighten conventional gun barrels using fibre composites, namely tensioned overwraps and flexural stiffening. This paper describes how the UK's composite materials technology, previously applied to conventional barrels, translates to the designs of fieldable EM launchers.

The next section describes progress in the construction and use of large-calibre launchers capable of firing tactical projectiles. This is followed by a review of present-day UK launchers, together with details of the development that has made them into multi-shot devices. Subsequently, the UK's advanced conventional barrel programme is described including the application of tensioned overwraps and thermal management, illustrating the logical extension of these technologies to the design of lightweight fieldable EM launchers. Finally, new concepts for lightweight EM launchers based on the novel use of tensioned overwraps are described. A parametric study of existing and proposed launchers is presented showing progressive development in launcher design with reference to mass, muzzle droop and inductance gradient. The benefits of thermal management for EM launchers also are discussed.

A BRIEF HISTORY OF THE DEVELOPMENT OF EM LAUNCHERS

The initial work on railguns was motivated by the curiosity of physicists ie as 'interesting physics experiments'. The first railguns were designed to allow rapid re-builds. They typically had a square or rectangular-bore cross-section, formed from tightly clamped and bolted core components, and required minimal machining either before or after assembly. The rails were made of plain copper, a natural first choice (given its good electrical conductivity and availability in flat bar form) but susceptible to gouging at relatively low velocities (often below 1kms^{-1}). Gouge formation became a major focus of the early work, so experimental programmes were embarked upon whereby the gun was rebuilt after every single shot. This routine satisfied the need to have a 'perfect' bore condition for each projectile launch, but carried the inevitable penalty of a readily strippable gun ie a general lack of structural rigidity.

As EM gun technology advanced, a second phase of 'more applied physics experiments' was embarked upon in the late 80's, with interest beginning to focus on the launch of projectiles with a meaningful military utility. Given that almost all gun-launched projectiles, to date, have been circular in cross-section, there was a natural move towards the development of round-bore EM launchers. The US Task B 90mm guns of the late 80s were the first significant exponents of round-bore EM technology at a relatively large calibre. The two launchers (one at Green Farm in California and the other at the Centre for Electromechanics in Texas (CEM)) differed completely in their design. The Green Farm gun (Ref 5) is relatively simple in its design, is fairly easy to rebuild but has relatively low radial stiffness. The CEM gun (Ref 6) has high radial and axial stiffness, a pressurised design which does not lend itself to rapid rebuild cycles, and a mass of around 30 tons.

Attempts to attain a reduction in mass from the CEM barrel were made with the Sparta 90mm guns (Refs 7, 8), where hydraulic pressure was used to maintain a state of compression in alumina ceramic segments surrounding the core. The approach was similar to that employed in the CEM Task B gun but with the outer, thick steel, pressure vessel of the Task B gun replaced by a stainless steel tube of minimal thickness supplemented with a composite over-winding. Firing trials showed up severe limitations in the Sparta barrels, but a number of useful design lessons were learned as a result.

Round-bore EM guns require post-assembly machining, usually by honing. This operation demanded a significant investment in machinery and operators. Because of the engineers' desire for as good a bore condition as possible for their shots, the Task B guns were generally re-honed after every firing (certainly in the early days). This produced a gun with an ever-growing bore size and a slow shot rate - one or two shots per week being typical. Nevertheless the two workhorse Task B guns, together with the expertise of the support teams, have contributed immensely to the development of the technology.

By the time that the UK Electromagnetic Launch Facility (EMLF) at Kirkcudbright came on line in 1993, a considerable amount of knowledge had been built up on large calibre EM firings. A generation of laboratory EM barrels has followed, using thin steel laminates to contain the core. The UK has fired several hundred EM shots in laminated steel EM barrels of different calibres in the 90s, confirming their suitability as laboratory guns. The challenge now is to introduce acceptable flexural properties, whilst also improving the core's radial stiffness and electrical properties and, most importantly, reducing the overall mass.

REVIEW OF UK EM LAUNCHERS

LAM40 5m and 8m Barrels

A 5m long, 40mm calibre laboratory barrel was conceived for installation at Fort Halstead in 1994 to help with rail and insulator materials selection. The design featured laminated steel containment, copper rails and glass/epoxy (GRP) insulators.

A technique was developed to build laminated containment modules by forming a structural bond between the steel plates. The adhesive used also provided the necessary plate to plate electrical insulation. Later this construction method was used to build an 8m long, 40mm calibre barrel at Kirkcudbright for high velocity firings. This design of module represented a major improvement in barrel structural integrity. To date in excess of 75 shots have been fired in these barrels with no deterioration of the modules observed. The rail material is copper-chrome-zirconium and full-length GRP pultruded insulators have been employed with excellent results.

90mm IAP Launcher at Kirkcudbright

This barrel was supplied to the UK EMLF at DERA in 1993 by International Applied Physics (IAP). It is an 8m long steel laminated construction with the original laminations secured by tack welds on their periphery. Laminated modules, approximately 0.5m long, are clamped in pairs, one above and one below the bore, to form the containment. A number of such pairs of modules complete the 8m length. Originally, the bore was formed from pure copper rails and the insulators were manufactured from an electrical grade of glass fibre reinforced plastic known as 10G40 (Tufnol). The use of a harder rail material, copper-chromium-zirconium, reduced the incidence of gouging thereby increasing the working velocity to 2000ms^{-1} (Ref 9). Alternative 10G40 insulator configurations have been tried to improve the bore dilation stiffness. However the dimensions in which the 10G40 insulator material is manufactured meant that joints were required along the length of the barrel which inevitably absorbed honing fluid and copper swarf leading to breakdown of the insulation.

The welded containment modules showed signs of deterioration after the first few shots (Fig 1). Individual steel plates deformed, both in the plane of the plate and in a warping mode. Shear displacement of the laminated assemblies occurred, similar to a pack of cards. Movement was also apparent between individual modules and between the modules and the support structure.
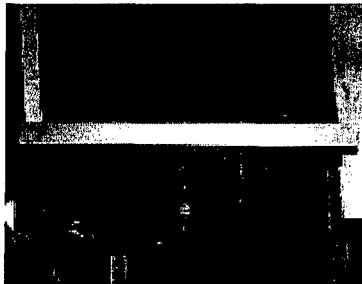

FIGURE 1

FIGURE 2

The cable attachment (Fig 2) was asymmetric below the centreline of the launcher, producing bending forces in the structure that were sufficient to cause permanent deformation of components. This effect has been noted for future launcher designs, where balanced forces will be essential to prevent deleterious effects on the structure and shot accuracy. The supporting I-beam also buckled forward of the breech interface.

Since its installation at DERA, the 90mm IAP launcher has been subjected to continuous development. The bowed module plates (Fig 1) did not compromise the radial stiffness of the launcher, but posed increasing difficulties during assembly. The original tack-welded containment modules of the IAP 90mm barrel were gradually replaced with structurally bonded modules (Fig 3) like those of the LAM40, but with thinner steel plates and bond lines to improve the barrel inductance gradient. The new laminated modules have been keyed to the sub-frame to prevent axial motion under firing load.

The insulators have evolved from segmented 10G40 through to full-length pultruded designs. The muzzle has been significantly strengthened to prevent damage from muzzle arc. The supporting I-beam has been extensively modified and reinforced to eliminate bending. A revised breech design with cable attachment either side of the launcher centreline has been fitted to reduce out-of-balance forces (Fig 4).
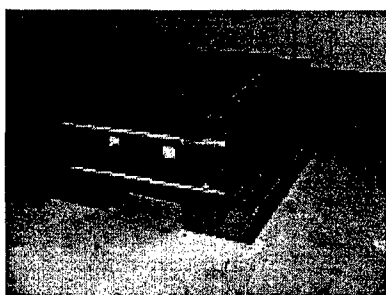

FIGURE 3

FIGURE 4

The limitations of the IAP 90mm launcher are now well known, but the progressive improvements have increased the launch energy to 8MJ, from an earlier limit of 5MJ, and have extended the life of the core components. Despite the difficulties encountered, over 210 shots have been fired to date at velocities of around 2000ms^{-1}, which was exceeded on many occasions. Nowadays, the launcher is honed once after building but not after subsequent firings.

The development programme described above illustrates the difficulty of constructing multi-part launchers, especially if are they are required to be easily rebuilt. The lessons learnt from the laboratory launchers are now being applied to the design of fieldable launchers.

90mm Task C Launcher at Kirkcudbright

This US (designed and built by CEM, (Ref 10)) barrel currently installed at the EMLF uses a laminated construction that has metal plates retained by a glass fibre reinforced composite overwrap. The rail material is are Glidcop, an oxide dispersion strengthened copper alloy produced by powder metallurgy, with fine alumina particles in the copper matrix. The insulators are full-length pultrusions of GRP featuring a braided skin over a core of uni-directional fibres. The rails and insulators are retained in position with a thin, shrink-fit, insulator before shaped steel plates are slid over the assembly. The plates are adhesively

bonded to each other, firstly in 5cm thick sub-assemblies, and then into 1m sections to form the 8m long barrel. The core and containment are bonded together by impregnating the entire assembly with epoxy resin. The steel plates primarily contain the rail loads during firing, with an additional thick, glass reinforced plastic overwrap providing structural stability and some degree of flexural stiffening. The whole barrel is mounted on a laboratory support structure. The Task C launcher (Fig 5) has been used at Kirkcudbright for proof firing projectiles approaching their design pressure and has also confirmed the results of the earlier accuracy trials from the IAP launcher.

FIGURE 5

ADVANCED UK CONVENTIONAL BARREL TECHNOLOGY

Selective strengthening and/or selective stiffening a steel tank gun barrel with advanced fibre composite materials has been the subject of much research in the UK. The technology is an extension of tensioned overwrap methods successfully applied to rocket motor construction (Ref 11).

The specific strength and specific stiffness advantages of composites over gun steels (in excess of 5:1) suggest that significant improvements in barrel performance could be gained by their use in gun barrel design. Compared to an all steel barrel, the higher specific strength of composites could be used to produce a gun barrel that has either a lower mass, or a higher working pressure for the same weight, or is longer for the same trunnion balancing moment. Alternatively, a combination of such benefits could be realised. Similarly, the higher specific stiffness of composites could be used to improve the accuracy of the gun system by reducing muzzle droop and increasing the natural frequency of the barrel. Furthermore, the local cross-section stiffness of the barrel could be modified to aid local tuning of the dynamic response.
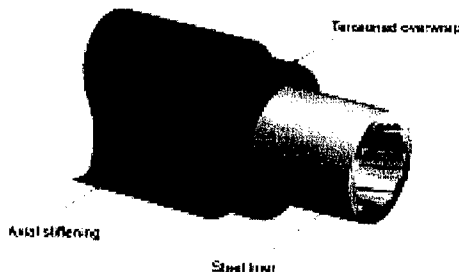

FIGURE 6

The technology developed by the UK comprises a carbon fibre composite wound under tension around a conventional gun steel liner. A diagram, identifying the various features of such a barrel, is shown in Fig 6.

The steel liner provides the wear and flame resistance, the pressure seal, and can accommodate the rifling if required. The function of the tensioned composite overwrap is to increase the hoop strength of the barrel, enhancing the pressure containment, and the outer sleeve increases flexural stiffness.

The UK has addressed the following fundamental issues that have enabled the potential benefits of this technology to be quantified, leading to the ability to optimise overwrapped gun barrel designs:

- A considerable amount of heat energy (in excess of 50% of the total available energy in the propellant) is released each time a round is fired. A significant portion of this heat is absorbed into the barrel, where it is dissipated via conduction and surface convection. Hence the thermal conductivity and heat capacity of the barrel will have a major impact on the barrel temperatures. Since fibre composites with organic matrices (e.g. epoxy resins) have a low thermal conductivity and heat capacity when compared with steel, there is a danger that the composite overwrap will fail to dissipate the heat at an adequate rate. This could result in barrel temperatures far exceeding those found in current all-steel guns. Note that temperatures in excess of 200-250°C are not untypical on the outside surface of a gun.
- To enable the composite overwrap and the steel liner to be used efficiently, bearing in mind the significant difference between their operating strains (steel <0.4, composites >1%) it is essential that the overwrapped barrel is in a state of pre-stress; compressive in the liner, tensile in the overwind. Furthermore, the presence of this pre-stress also alleviates the thermal expansion mis-match problems, particularly at low temperature, where the steel will contract significantly more than the tensioned overwrap.
- The fatigue life of overwrapped barrels needs to be commensurate with that for the all-steel barrels. Pre-stressing the liner is essential in meeting this requirement.
- Accurate structural analysis procedures must be developed in order to design an efficient thick-walled, metal lined, composite overwrapped gun tube. These procedures need to take into account anisotropic material properties, the pre-stress induced during fabrication and the differential thermal expansion behaviour.

In order to address the key technical areas associated with this technology, a comprehensive R & D programme was initiated in 1987. To ease the technical risks and to provide confidence in the 'guns community', the programme was divided into the following phases:

- Development of a PC-based gun barrel design package to provide the structural analysis, barrel heating, frequency and droop calculations with easy to use pre- and post-processors applicable to composite overwrap barrels.
- Overwrap material selection considering both fibre types and high temperature resin systems.
- Laboratory evaluation of 30mm and 120mm calibre overwrapped barrel sections in static and fatigue tests.

- Firing trials of overwrapped 30mm calibre 'RARDEN' and 120mm calibre tank guns with barrel heating and dispersion assessment.

Application of Gun Barrel Design Software

The software has been used to study overwrap technology in relation to 30mm, 40mm, 120mm calibre and 140mm calibre barrels. Useful improvements to mass, droop and frequency response have been predicted. Certain scenarios permit the barrel length to be extended giving useful improvements to range and accuracy. The highest rates of fire are predicted to cause cook-off problems that might require thermal management. Full details of the phased development programme are reported elsewhere (Ref 12).

Thermal Management

Barrel heating can prevent sustained high rates of fire with modern artillery. Firstly, the barrel may become hot enough to cause charge 'cook off' (~180°C) and/or melting of the shell filling (80°C). Secondly, high temperatures can cause unacceptable wear rates, and in extreme cases, a loss of mechanical strength of the barrel materials.

During the firing cycle of the gun, approximately 5% of the charge energy is imparted to the inside surface of the barrel wall as heat. This heat is conducted through the barrel wall and is dissipated to the atmosphere through natural convection from the exterior barrel surface. Due to the poor heat transfer to the surrounding air, the rate of heat loss from the barrel is low compared to the rate of heating. As a result, rapid or sustained firing will quickly heat the barrel to a temperature beyond that which the ammunition can be safely loaded and fired. In extreme circumstances the gun may be out of action for periods up to 24 hours before its temperature returns to ambient.

Considering artillery systems, studies have shown that improved performance will require greatly increased charge energies. The current levels of heat input to AS90 (the UK's in service 155mm, self-propelled, howitzer) is around 2.4MJ (per shot), with near future systems 2.7MJ and next generation 4.2MJ.

A system study has indicated that active thermal management could be of 'high' benefit to the AS90 system. Benefits are expected to be a higher sustained rate of fire with reductions in risk of cook-off, barrel wear at the commencement of rifling, barrel bend, bore choke, muzzle velocity variations and thermal signature.

The UK programme at DERA continues to investigate thermal and structural testing of full-calibre, 155mm, mid-wall cooled barrels (Fig 7).

FIGURE 7

DEVELOPMENT OF FIELDABLE EM BARREL CONCEPTS

Research to date has focussed on enhancing the structural integrity of the existing launcher systems, whilst developing construction methods and materials applicable to future, lightweight, electrically efficient, fieldable EM barrels. Construction methods have centred on overwound designs as a logical extension of the expertise developed for conventional barrels. Structural stability and bore dilation under dynamic loading are key factors in determining the projectile launch dynamics, accuracy and dispersion inherent in a gun system. Consequently, launcher concepts are analysed using structural and electromagnetic finite element modelling and the results are validated by instrumented trials using short barrel test sections.

Specific technologies under consideration include tensioned overwraps, both organic fibres and metals, and methods for pre-loading the core in compression using hydraulics. Short lengths of promising core containment concepts have been built and tested to begin to identify a practical configuration for an advanced EM barrel, working towards a fieldable system. Parametric studies (mass breakdown, stiffness, barrel droop, frequency response, etc) have been performed for existing EM barrel configurations and future barrel concepts. Whilst the parameters might not match future specifications in absolute terms, they are felt to be sufficiently representative to demonstrate the relative merits of the various EM launcher concepts.

Laboratory EM launchers have been made previously with varying degrees of bore radial stiffness, both less than and greater than conventional ordnance. However, none of them has provided any significant inherent flexural stiffness; this is the predominant additional requirement of a fieldable launcher. Lightweight materials with high strength and modulus are candidates for fieldable launcher construction. However, many promising materials are not available in the size required, and often the available materials data is not relevant to EM launcher design. DERA has ongoing programmes to develop appropriate forms of materials, and acquire materials data for the design of fieldable launchers.

Design Concepts

Four concepts for 90mm calibre fieldable barrels have been produced in outline. For the barrel cross-section shown in Fig 8, the flexural stiffness is provided by a fabricated structure which is independent from the hoop-wise composite tensioned overwrap containment. The insulators are of a two-part construction to provide the advantages of both GRP and ceramics. The inner insulator is sufficiently elastic and dimensioned such that the pre-stress applied by the overwrap will compress it against the rail. The outer insulator is a stiffer non-conductive material, which enables the amount of pre-stress required from the containment to be provided without deforming the bore geometry. With this configuration, the pre-stressed inner insulator moves with the rail during firing.

The fabricated longitudinal support would also facilitate the integration of the barrel into the vehicle using a conventional cantilever cradle mounting arrangement.

In the launcher configuration shown in Fig 9 the copper rail/ceramic insulator interface has been keyed longitudinally to minimise relative displacement under firing load. During manufacture, an insulating material would be wound around the core (not shown in the schematic) after which an insulated steel wire overwrap is added to react the dilation of the rails and insulators during firing. The next outer layer is of tensioned composite overwrap to

augment the steel windings. Finally, a steel or titanium fabricated structure will be clamped round the barrel to provide flexural support.
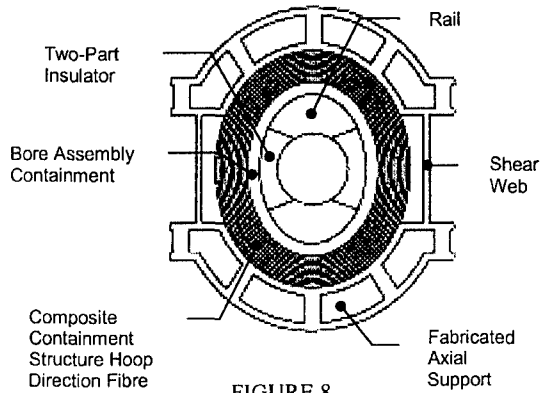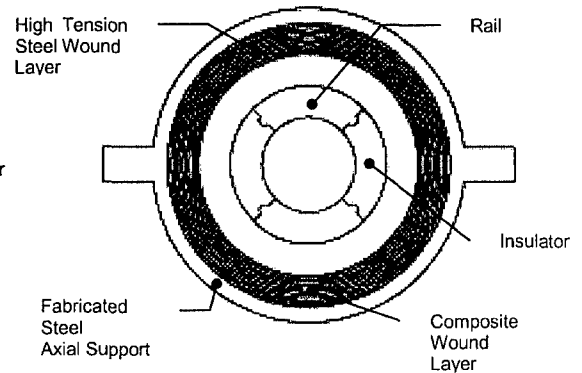

FIGURE 8

FIGURE 9

The composite elliptical containment shown in Fig 10 may provide a better method of controlling rail movement than circular overwrapped designs and the rail configuration employed increases the inductance gradient compared to contemporary 90mm launchers. The latter is a significant result since system study modelling has shown that launcher efficiency is the most important factor contributing to overall system efficiency. The proposed barrel features a high performance carbon fibre reinforced plastic (CFRP) overwrap and a carbon fibre composite, longitudinally stiffened sleeve whose thickness is calculated to obtain muzzle droop comparable to a conventional 120mm tank gun barrel. As yet the barrel cross-section is assumed to be constant along the length, but a future development will be to reduce weight and decrease droop further by reducing rail and containment size nearer the muzzle.
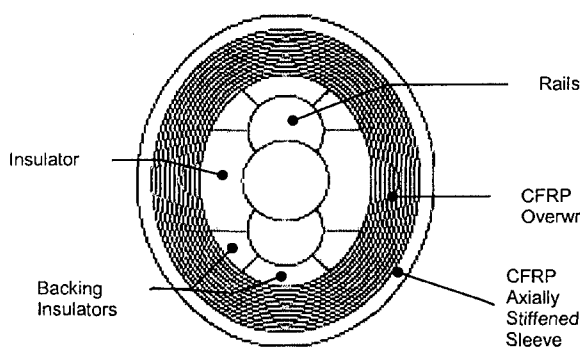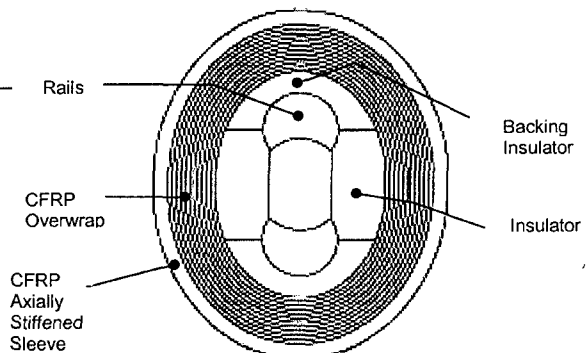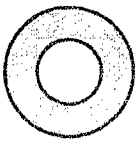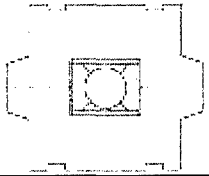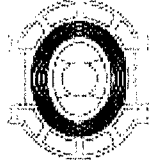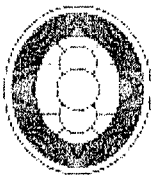

FIGURE 10

FIGURE 11
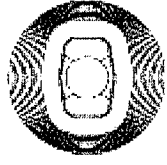
The UK effort has concentrated mainly, to date, on round-bore EM projectiles and guns. Rectangular-bore guns have certain advantages over round-bore configurations (Ref 13). For example, the efficiency of electrical contact is probably higher for a rectangular-bore because the current is distributed more evenly across the rail width. Muzzle droop may be less because the rails can be positioned more favourably with respect to the neutral axis of the

barrel in bending. The inductance gradient may be higher depending on the ratio of rail spacing to overall rail width. However, containment design for a rectangular-bore is likely to be more difficult, as will be bore finishing operations such as honing. An elliptical-bore (to match the elliptical containment described above) has similar disadvantages because of difficulties with bore finishing. However, a hybrid 'oval' bore, where the rails of a round-bore launcher are moved further apart, would have a desirable inductance gradient whilst the flat sides of the oval would ease the structural design of insulators thereby permitting higher rail pre-load. Projectile design is simplified being an evolution of successful round-bore designs and the possibility of shot rotation in-bore would be avoided. Such a scheme is shown in Fig 11.

EM Launchers Parametric Study

Table 1 contains the results of a parametric study of present EM launchers and lightweight EM launcher schemes in relation to the L30, 120mm calibre barrel fitted to the UK Challenger 2 main battle tank. Barrel length, mass, flexural stiffness, droop under self-weight and inductance gradient have been evaluated to enable realistic comparisons to be made between the various designs.

Table 1

Barrel Design	Total Barrel Mass	Flexural Stiffness EI	Tip Deflection*	L' Value (μH) from Stored Energy	Barrel Cross-Section
120mm calibre Challenger 2 L30 In-service conventional barrel	1.00	1.00	1.00	-	
IAP 90mm calibre laminated laboratory barrel	8.92	7.38	2.21	0.455	
TASK C 90mm calibre laminated laboratory barrel, glass/epoxy overwrap	1.91	0.64	5.44	0.461	
90mm calibre composite barrel concept with fabricated steel support	1.14	2.11	0.99	0.367	
90mm calibre wire wound barrel concept with steel tube support	1.46	1.49	1.79	0.136	
90mm calibre elliptical overwrap barrel concept with longitudinally stiffened external sleeve	1.28	2.33	1.00	0.486	
100mm calibre oval-bore barrel concept with elliptical overwrap and longitudinally stiffened external sleeve	1.32	2.49	0.97	0.518	

* - Assuming barrel is encastré at the breech-end. EM barrels assumed to be 8m long

For the EM launchers, the mass has been determined from finite element models of the cross-sections and the barrel length. The flexural stiffness (EI) is the summation, for all components, of the product of the Young's modulus in the axial direction and the second moment of area about the neutral axis of the barrel in bending. Tip deflection is calculated assuming that the barrel is supported as a cantilever and using the appropriate formula based on Engineers' Bending Theory (Ref 14). The barrel inductance gradient, L', has been estimated from electromagnetic finite element modelling of the barrel section; this technique correlates well with published data (Ref 10).

The laboratory launchers LAM90 and, to a lesser extent, Task C, are included to emphasise how heavy and flexible such designs are, and that their deployment as fieldable barrels, ie without their laboratory stands, is completely unrealistic. The laminated steel construction method used appears inappropriate for lightweight barrels.

The four fieldable barrel concepts proposed all feature tensioned overwrap technology combined with separate flexural stiffening. Their masses are comparable with that of a conventional 120mm barrel, as are their tip deflections. It is noteworthy that the oval-bore, fully composite, barrel has an increased L' of 0.518, compared to the round-bore designs. The wire-wound barrel concept has a disappointing L' value of $0.136\mu Hm^{-1}$ at present. However, this concept is part of an ongoing development programme investigating active management of bore dilation. Controlling the rail movement during firing is extremely difficult with overwrapped barrels. For example, Task C barrel contains the rail loads mostly by the steel laminations; the overwrap only providing additional structural stability. However, the predicted rail dilation for the composite overwrapped, oval-bore, barrel (Fig 11) is commendably low at about 1.2 times the breech-end bore dilation at the gun design pressure for L30, considering a typical hypervelocity EM gun firing scenario. The bore dilation is affected by many elements of the barrel design, but is strongly influenced by the choice of insulator material.

Hydraulic Bore Loading

Understanding the movement of the core components during firing is fundamental in the design of fieldable EM launchers. Finite element modelling of candidate barrel sections has been backed-up by bore dilation measurements on barrel sections. In order to simulate the internal forces that act in the launcher during firing, a bore loading mandrel has been developed which applies a load evenly along the launcher rail length. This mandrel has been successfully demonstrated up to levels of pressure equivalent to the working pressure in a conventional tank gun barrel. The force distribution has been validated through tests in a thick-walled steel cylinder, instrumented with strain gauges and non-contact fibre-optic displacement sensors, Fig 12.

Pre-loading the core of the EM launcher in compression can be used to control bore dilation during firing. The two principal methods that have been investigated are so-called 'flat jacks' (Ref 15) and tension overwinding (described previously). A flat jack (Fig 13) comprises two plates, seam welded about their edges and pressurised internally. Flat jacks have been successfully incorporated into a 90mm laminated launcher module to pre-load the core. The jack is placed directly behind the rail and reacts against the containment module. The behaviour of the core components, in particular the insulators, can be assessed using this technique.
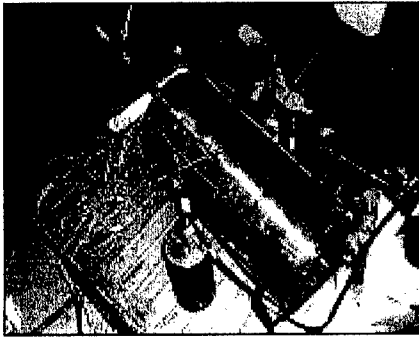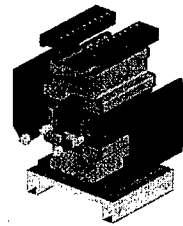
FIGURE 12

FIGURE 13

Thermal Management and Rail Materials

The present generation of EM launchers uses monolithic rails with uniform properties along the whole length and across the whole section. There are at least three separate sections along the length of the barrel requiring different properties - the insertion region, the high current density region and the exit. The rail containment in the high current density region needs to be much stiffer than other regions of the barrel and redistribution of the mass in the form of tapered rails would seem appropriate. However for accuracy, the exit region, which is subjected to lower current densities, must retain dimensional precision. Steel might be useful here as it would also provide resistance to gouging.

Co-extrusion of rail materials appears attractive and samples of aluminium-cored copper have been procured. EM modelling has shown (Fig 14) that in a round-bore gun, the current density is higher at the edges of the rails than in the interior, allowing a lighter, lower conductivity material to be introduced into the core. Clearly the weight-saving is advantageous in the design of a fieldable launcher.
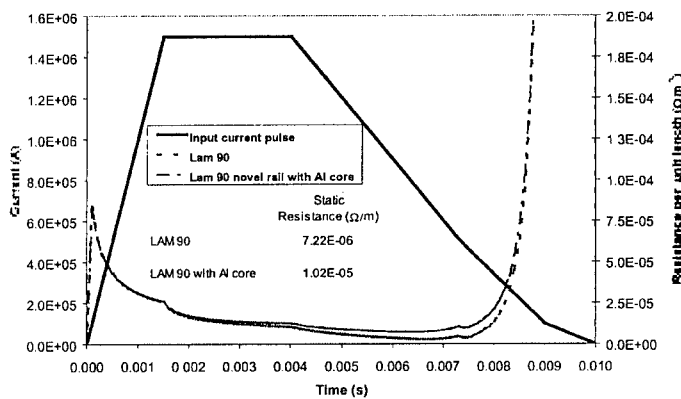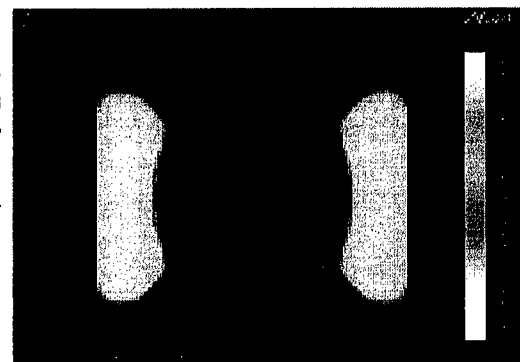

FIGURE 14

The techniques described earlier for the thermal management of conventional barrels are likely to be required for fieldable EM launchers. Thermal management of the rails would seem essential to minimise changes in rail conductivity under variable ambient conditions, to control the increase in rail temperature during repeated firings, and possibly to increase the conductivity and strength by suitable cooling below ambient temperatures. Water cooling may reduce rail wear by ensuring that any melting is immediately quenched back to solid alloy. Operating at modest cryogenic temperatures could provide considerable advantages, even if the high-current density section only was cooled. It may allow considerable improvements in system efficiency permitting hyper-velocities to be achieved for tactical projectiles without recourse to exotic materials, if the engineering and practical issues can be overcome.

CONCLUSIONS AND NEXT STEPS

The brief history of EM launcher developments, provided in this paper, serves to indicate that much of the technology still remains rooted in 'physics experiments', for reasons that are readily understood. There is a significant challenge in front of the community to move the debate towards concepts which can be translated into 'fieldable EM Guns' in the true sense of the words. Whilst the remaining fundamental physics issues should not be underestimated (eg when/if transition in-bore is acceptable), the level of maturity is now sufficient to switch attention elsewhere.

The intent of this paper has been to indicate that the conventional (ie powder) gun design community is not static, and recent advances in that arena may well form the basis for bridging the technology gap which the EM gun community must cross, if it is to have a future. It is now timely to begin to address the practical gun design issues, those of stiffness, mass distribution, materials selection, fabrication route, shot/barrel dynamics and mounting within a vehicle. The singular most effective next step is to bring together the physicists and gun designers such that the next generation of EM launchers is designed and built to be a prototype 'towards fieldable' EM launcher, and not another 'physics experiment'.

ACKNOWLEDGMENTS

REFERENCES

1.   Robert J. Taylor, "Influence of Combat Vehicle System Constraints on EML Technology Development," *IEEE Transactions of Magnetics, Vol 35, No. 1*, 473-478, January 1999
2.   K. G. Cook et al, "Subscale Rotor Spin Testing for Compulsator Component Development," *IEEE Transactions of Magnetics, Vol 35, No. 1*, 277-282, January 1999

3. John M. Juston, "A High Performance Railgun Launcher Design," *IEEE Transactions of Magnetics, Vol 33, No. 1,* 566-570, January 1997
4. Alexander E. Zielinski, "Improved Integrated Launch Package Ballistic Performance," *IEEE Transactions of Magnetics, Vol 35, No. 1,* 124-129, January 1999
5. S. Rosenwasser, "Recent Advances in Large Railgun Structures and Materials Technology," *IEEE Transactions of Magnetics, Vol 27, No. 1,* 444-451, January 1991
6. R. Zowarka et al, "9MJ Laboratory Gun and Range at the University of Texas at Austin," *IEEE Transactions of Magnetics, Vol 25, No. 1,* 653-661, January 1989
7. M. Holland et al, "Advanced Railgun Experimental Test Results and Implications for the Future," *IEEE Transactions of Magnetics, Vol 29, No. 1,* 419-424, January 1993
8. Vrable et al, "Design and Fabrication of an Advanced Lightweight High Stiffness Railgun Barrel Concept," *IEEE Transactions of Magnetics, Vol 27, No. 1,* 470-475, January 1991
9. D. Munday, D. G. Jones and K. J. A. Mawella, "Metallographic Studies on Rails Removed from the DRA Electromagnetic Launch Facility at Kirkcudbright," *5th European Symposium on Electromagnetic Launch Technology, Toulouse, France,* Paper No. 93, 10-13 April 1995
10. J. J. Hahne, J. H. Herbst and J. L. Upshaw, "Fabrication and Testing of a 30mm and a 90mm Laminated, High L' Railgun Designed and Built at CEM-UT," *IEEE Transactions of Magnetics, Vol 31, No. 1,* 303-308, January 1995
11. J. Cook, A. Groves, R. Hayman, A. Howard, "Modern Approach to Overwound Structures," *Plastics, Rubber and Composites, Vol 28, No. 5,* 259-267, 1999
12. M. J. Hinton et al, "Advanced Materials for Gun Systems, to be presented at," *10th U.S. Army Gun Dynamics Symposium, Plenary paper,* 23-26 April 2001
13. Richard A. Marshall, "Railgun Bore Geometry, Round or Square," *IEEE Transactions of Magnetics, Vol 35, No. 1,* 427-431, January 1999
14. Warren C. Young, "Roarke's Formulas for Stress and Strain," Published by McGraw-Hill Book Company, 1989
15. M. D. Werst et al, "Design and Testing of a Rapid Fire, Lightweight, Ultrastiff Railgun for a Cannon Calibre Electromagnetic Launcher System," *IEEE Transactions of Magnetics, Vol 31, No. 1,* 365-370, January 1995